October 13, 1989

To: Dr. M.M. Reischman, Director, Mechanics Division, Office of Naval Research
From: A. Needleman
Re: Yearly Summary of Research for FY89

Title: Ductile Failure
Grant Number: N00014-89-J-3054
Scientific Officer: Dr. R. Barsoum

Research Summary

Work under this grant has proceeded in two areas: (i) combined experimental and numerical studies of the plastic response of metal matrix composites in collaboration with Professor S. Suresh and (ii) analyses of dynamic crack growth in porous plastic solids in collaboration with Dr. V. Tvergaard of the Technical University of Denmark.

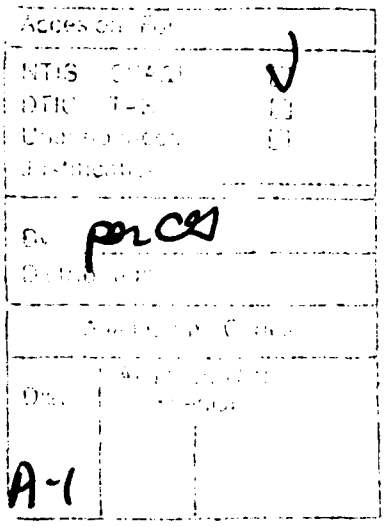
In work that began under contract N00014-86-K-0262 and finished under the present grant, dynamic crack growth was analyzed numerically for a plane strain double edge cracked specimen subject to symmetric impulsive tensile loading at the two ends. The material behavior is described in terms of an elastic-viscoplastic constitutive model that accounts for ductile fracture by the nucleation and subsequent growth of voids to coalescence. Two populations of second phase particles are represented, including large inclusions or inclusion colonies with low strength, which result in large voids near the crack tip at an early stage, and small second phase particles, which require large strains before cavities nucleate. The crack growth velocities determined were entirely based on the ductile failure predictions of the material model, and thus this study is free from ad hoc assumptions regarding appropriate dynamic crack growth criteria. Adiabatic heating due to plastic dissipation and the resulting thermal softening were accounted for in the analyses. Different prescribed impact velocities, inclusion spacings and values of the inclusion nucleation stress were considered. Predictions for the dynamic crack growth behavior and for the time variation of crack tip characterizing parameters were obtained for each case analyzed.

In the above work, which has been submitted for publication, attention was confined to uniformly spaced inclusion distributions. In continuing work, the effect of non-uniform inclusion distributions has been analyzed. The aim here is to quantify distribution effects on toughness. Our results indicate that both the COD at the original crack tip needed to grow the crack a fixed amount and the crack speed scale linearly with root mean square inclusion spacing, to a good approximation. At fixed mean inclusion spacing, we obtain an increased resistance to crack growth with increasing root mean square inclusion spacing. Hence, in the circumstances analyzed here, resistance to crack growth increases with increasing deviation from uniformity. This can be contrasted with experimental and theoretical results which demonstrate that deviations from a uniform porosity distribution tend to decrease ductility. A manuscript describing this work is in preparation.

The deformation characteristics of ceramic whisker- and particulate-reinforced metal-matrix composites are being studied experimentally and numerically in collaboration with Professor S. Suresh with the objective of investigating the dependence of mechanical properties on the matrix microstructure and on the size, shape, and distribution of the reinforcement phase. Our previous

work showed that the development of significant triaxial stresses within the composite matrix, due to the constraint imposed by the reinforcements, provides an important contribution to strengthening under monotonic uniaxial loading. In particular, our numerical results delivered a mechanistic rationale for experimentally observed trends on: (i) the effects of reinforcement morphology and volume fraction on yield and strain hardening behavior of the composite, (ii) the pronounced influence of reinforcement clustering on the overall constitutive response, (iii) ductile failure by void growth within the composite matrix, (iv) the insensitivity of the yield strength of the composite to changes in matrix microstructure, and (v) the dependence of ductility on the microstructure of the matrix and on the morphology and distribution of the reinforcement. In ongoing work the effects of superposed hydrostatic stresses and of cyclic deformation histories are being investigated.

Alan Needleman
Professor of Engineering



List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals:

R. Becker, A. Needleman, S. Suresh, V. Tvergaard and A.K.Vasudevan, "An Analysis of Ductile Failure by Grain Boundary Void Growth," *Acta Metallurgica*, **37**, 99-120 (1989).

T. Christman, A. Needleman, S.R. Nutt and S. Suresh, "On Microstructural Evolution and Micromechanical Modelling of Deformation of a Whisker-Reinforced Metal-Matrix Composite," *Materials Science and Engineering*, **107A**, 49-61 (1989).

A. Nacar, A. Needleman and M. Ortiz, "A Finite Element Method for Analyzing Localization in Rate Dependent Solids at Finite Strains," *Computer Methods in Applied Mechanics and Engineering*, **73**, 235-258 (1989).

2. Papers Submitted to Refereed Journals and not yet Published:

T. Christman, A. Needleman and S. Suresh, "An Experimental and Numerical Study of Deformation in Metal-Ceramic Composites," *Acta Metallurgica*, to be published.

A. Needleman and V. Tvergaard, "An Analysis of Dynamic, Ductile Crack Growth in a Double Edge Cracked Specimen," submitted for publication.

3. Presentations:

a. *Invited*:

A. Needleman, Steel Research Group Workshop, Evanston Illinois, November 1988.

A. Needleman, Institute for Mathematics and Its Applications, Minisymposium on Plasticity, Minneapolis Minnesota, February 1989.

A. Needleman, 7th International Congress on Fracture, Houston Texas, March 1989.

A. Needleman, Army Symposium on Solid Mechanics, Newport Rhode Island, May 1989.

A. Needleman, NATO Advanced Study Institute on Disorder and Fracture, Corsica France, June 1989.

A. Needleman, ASME Summer Applied Mechanics Meeting, La Jolla California, July 1989.

A. Needleman, Euromech 252, Glasgow Scotland, August 1989.

b. *Contributed*:

A. Needleman, 7th International Congress on Fracture, Houston Texas, March 1989.

4. Books (and sections thereof):

A. Needleman and V. Tvergaard, "Analyses of Crack Growth in Ductile Solids," in *Proceedings of the 7th International Conference on Fracture*, (ed. by K. Salama *et al.*), Pergamon Press, 2011-2018 (1989).

A. Needleman and S. R. Nutt, "Void Formation in Short-Fiber Composites," in *Proceedings of the 7th International Conference on Fracture*, (ed. by K. Salama *et al.*), Pergamon Press, 2211-2218 (1989).

Y. Leroy, A. Needleman and M. Ortiz, "An Overview of Finite Element Methods for the Analysis of Strain Localization," in *Cracking and Damage: Strain Localization and Size Effect*, (ed. by J. Mazars and Z.P. Bazant), Elsevier Applied Science, 269-294 (1989).

5. Books (and sections thereof) not yet Published:

A. Needleman, "Damage Evolution, Instability and Fracture in Ductile Solids," in *Disorder and Fracture*, (ed. J.C. Charmet), to be published.

List of Honors/Awards

A. Needleman, elected Fellow, American Society of Mechanical Engineers, 1989.

Publications/Patents/Presentations/Honors

Papers submitted to refereed journals (and not yet published): 2

Papers published in refereed journals: 3

Books (and sections thereof) submitted for publication: 1

Books (and sections thereof) published: 3

Patents filed: 0

Patents granted: 0

Invited presentations at topical or scientific/technical society conferences: 7

Contributed presentations at topical or scientific/technical society conferences: 1

Honors/Awards/Prizes: 1

List of Participants

A. Needleman, Professor of Engineering
A. Nacar, Graduate Student Research Assistant